CHAPTER ONE

OVERVIEW OF THIS THESIS

1.1 Background to this thesis

This Ph.D. project was inspired by the desire to understand new types of seismic waveforms acquired at Stromboli volcano in 1992 by scientists at the University of Leeds [*Neuberg et al.*, 1994]. The short-period (> 0.5 Hz) wavefield has been studied extensively, and signals (explosion quakes) have been identified which correspond to eruptions, and usually occur several times each hour. However, broadband recordings of these same signals show previously unobserved very-long period (VLP) phases (T=2-20 s) when a high pass filter at 100 s is applied [*Neuberg et al.,* 1994; *Neuberg and Luckett*, 1996; *Luckett*, 1997]. These waveforms are much simpler and an order of magnitude stronger than the corresponding short-period signals, consisting of two or three distinct phases. The characteristic feature of these VLP phases is that they indicate a slow expansion and then a rapid contraction of the volcanic source immediately prior to eruptions.

Analysis of data acquired in 1995 demonstrated that even longer period (20-60 s) phases are associated with eruptions at two of the vents. A high pass filter at ~ 50 s reveals these phases well, which are not really waves at all, since they are recorded in the very near field, and in this thesis they are called *deformation* phases. These phases indicate inflation of the volcanic edifice prior to an eruption, and deflation after the eruption.

A detailed analysis of VLP phases recorded in 1992 was conducted by *Luckett* [1997], with particular emphasis on locating the source using classic seismological tools such as travel-time inversion and polarization analysis. This thesis was originally intended to complement that study. The strategy was to develop techniques for modelling volcano-seismic sources, and then apply those techniques to investigation of the VLP and deformation signals at Stromboli (and possibly elsewhere). It was clear from that outset that there were basically two parts to the modelling problem:

1. There is the problem of how magmatic fluids move, for it is generally believed that long-period signals (anything less than ~2 Hz) are caused by the pressure changes related to the movements of magma and gas in volcanic chambers and conduits. Unfortunately, while there is extensive literature on various aspects of bubble dynamics and other processes that are related to eruptions, the corresponding pressure changes are rarely considered, which would be the first step in terms of estimating the resulting seismic displacements.

2. The second part is to model effects of deformation and wave propagation in the near field. When seismic waves are generated at the conduit wall, several wave phenomena conspire to complicate the wavefield with the result that the recorded seismic waveforms cannot be considered a record of pressure change within the conduit. The most important phenomena are the free-surface interaction [Section 3.2.4] and near-field effects [Section 3.2.6]. It's also important to consider tilt [Section 2.3.4] when studying long-period data since strong tilt-induced signals may be superimposed on the displacement signal in the near-field.

In volcano seismology, the seismic source is usually assumed to be a point source, even though the data may be consistent with other 'source types'. The average repose period at Stromboli was approximately 10 minutes during the interval of time that broadband seismic data were acquired. It is therefore distinctly possible that deformation and VLP phases, which have durations of more than a few seconds, are related to the movement of magma recharging the system prior to the next eruption (particularly as these phases commence immediately before eruptions). During such a process, the whole conduit would act as a source, and it would be incorrect to model this as a point source, since the source region may subtend a large angle at the stations. A scheme is developed in which any simple volcanic process can be classified as either a point source, a line source, a moving point source or an expanding line source, depending on how pressure in the source region changes as a function of depth and time. In order to distinguish between these different 'source types', data from a well-distributed seismic network and synthetic modelling are required. Derivation of a suitable modelling method [Chapter 4] became the main part of this work.

Waveform modelling is not attempted in this thesis because it proved to be too complicated. The problem is that there are so many physical parameters that can be adjusted, and some of these are very poorly constrained, so the range of possible models is enormous. The inherent non-uniqueness means that it is easy to 'fix it' so that several completely different models match the waveform recorded at one station, rendering the results meaningless. It is, however, relatively to calculate the size of pressure changes consistent with recorded data for different volcanic processes (at least if the initial dimensions of the source region are known). This 'amplitude modelling' provides a simple and useful tool for rejecting source models based on the argument that they cannot generate signals of the size observed.

1.2 Aims of this thesis

The aims of this thesis are:

(1) to investigate the origin of VLP and deformation eruption-related phases at Stromboli,

(2) to develop modelling techniques which enable parameters of the seismic source (e.g. source type, source location, source radius, pressure change) to be constrained, and can be applied to all volcanoes,

(3) to provide a first-step in answering questions like 'what is the seismic signature of rising magma?'.

1.3 Why study Stromboli?

Although the methods developed in this thesis are applicable to all volcanoes, they are only applied to Stromboli in this thesis. Stromboli is considered to be one of the simplest volcanic systems in the world, and as such it is one of the most studied volcanoes in the world. However, it is the volcanoes with more viscous magma which erupt relatively infrequently that pose by far the greatest threat to human lives, and to the global climate, so to what extent is it useful to study Stromboli?

It may be argued that since a greater variety of processes occur at these more dangerous volcanoes, then whatever we learn about Stromboli may be of little use. However, the very fact that only some of these processes occur at Stromboli can be an advantage. By reducing the number of unknowns, we have a better chance of uncovering the role of each unknown parameter. Once a good understanding of these unknowns, and Stromboli in general, exists, we will be much better placed to understand those more complex and dangerous volcanoes. Laboratory models also offer the chance to isolate a subset of these different processes and should support research on simple volcanic systems such as Stromboli. At the same time, the more complex volcanoes should not be ignored, and in particular should be heavily monitored, but research conducted on simple volcanoes such as Hawaii and Stromboli is likely to be more fruitful.

1.4 How this work contributes to volcano-seismology

The main contribution of this thesis would appear to be the k-ω method, which can be used to model moving and extended sources in addition to a stationary point source. However, the significance of the decay law method should not be underestimated. It is comparable to the Mogi method in its ease of use, but includes both near and far field terms, and is also naturally extended to line sources. Both methods are applicable to all volcanoes.

However, the main message that should be taken from reading this thesis is that if we are ultimately to link volcano-seismic signals to the underlying magmatic processes and really understand how volcanoes work, we need open our minds. We need to develop seismic wavefield modelling techniques that can deal with realistic sources (corresponding to actual volcanic processes), rather than point sources. We need to be sure these techniques take account of both near and far field terms. Tilt induced signals and the effects of the free surface should be removed routinely; to date not a single paper does this! And finally we should use our data to extract the maximum possible information we can about the seismic source, rather than just trying to determine the position of the seismic source which really doesn't help us to learn much about the underlying physical processes at all.

1.5 Structure of this thesis

The thesis is presented more or less in the order that work was carried out, but only because that happens to be the most logical way to present it. Each chapter has an introduction and a summary to link the chapters and to help with cross-references.

Chapter 2 begins with a brief overview of the main geographical and historical features of Stromboli taken from several published sources. A brief discussion of the activity during the 1992 and 1995 Leeds field experiments comes mainly from work by Leeds scientists.

Section 2.3 covers the seismicity at Stromboli. The description of the reconstitution process is entirely original and following this there is a review of what is known about short period signals and VLP signals at Stromboli, with a discussion about the relative merits of each. A very brief discussion of tremor at Stromboli is given for completeness, but tremor signals are not modelled in this thesis.

Section 2.4 discusses what can be inferred about the geometry of the magmatic system at Stromboli from thermodynamic, petrological and degassing evidence, which appears to suggest the existence of a shallow magma body, perhaps no more than 200 m below the vents. Relatively little published work exists on this topic, although it is crucial for modelling.

Finally in Section 2.5 Strombolian activity is discussed particularly with regard to how it relates to Hawaiian activity. The discussion then switches to identifying volcanic processes which may generate detectable seismic energy; again this work is entirely original and is necessary in order to constrain possible source models used throughout the rest of the thesis.

In Chapter 3 the problem of relating observed seismic signals to the physical processes that occur in the magmatic system is examined. All the work in this chapter is original work.

The seismic signature is usually considered to be directly proportional to pressure changes within the volcano, but as wavefield interacts with the conduit wall, propagates through the solid, and interacts with the free surface, it gets distorted. These effects are examined in Section 3.2, with the conclusion that VLP waves can be modelled differently than short period waves.

The resultant wavefield is, of course, critically dependent on the source. The importance of considering different source types is emphasised in Section 3.4. Four source types are identified, including two types of moving source. This work is completely original; a point source is almost universally assumed in volcano seismology. The importance of choosing the correct source type is demonstrated in a simple experiment where synthetic data from a moving point source is inverted assuming a (stationary) point source. The resulting hypocentres are so inaccurate that they are completely useless.

Section 3.3 on decay law modelling is entirely new, and is an attempt to include both near and far field terms in a simple modelling technique, which can be applied very quickly to volcano-seismic data in order to estimate the magnitude of pressure changes in the source region. Separate models are derived for a point source and a line source, and these models are both applied to VLP phases recorded at Stromboli in 1992.

In Chapter 4 more sophisticated modelling (the k-ω method) is presented. The method assumes the conduit is a vertically oriented, partially viscous fluid filled cylinder embedded in an infinite solid. Perturbations in matched boundary conditions at the conduit wall allow moving and extended sources to be modelled in addition to point sources. This is an important breakthrough in volcano seismology. Even if these other sources are found not to be applicable to volcano-seismic signals, at least they can now by rejected on a quantitative basis, rather than through laziness or ignorance.

The method was derived from first principles, but followed an outline given by *Theisse* [1996], However, the treatment given in this thesis is much more thorough and rigorous, and uses a much improved nomenclature. The method has also been extended to include several new source types, including advective overpressure which is described by a line source, and a rising magma source with a pressure gradient; these are derived in full. Some of the mathematics for this method cannot be found in previously published work and is included in Appendices.

The method is thoroughly tested in Section 4.5, which is entirely original work, prior to its application to Stromboli in Chapter 5.

In Chapter 5 the k-ω method is applied to Stromboli. All the work and ideas in this chapter are new. Using 12 hours of data from the 1995 deployment, the six largest VLP signals corresponding to vent 1 eruptions are measured. Synthetic seismograms are then computed using the *k*-ω method for point sources, line sources and rising magma sources. The amplitudes of these synthetic seismograms (at each station) are compared with the amplitudes of VLP seismograms recorded at Stromboli in 1995; the aim is to constrain the seismic source and estimate pressure changes. Disappointingly it is found that moving sources are not consistent with VLP signals at Stromboli.

In Chapter 6 the important results and conclusions of the previous chapters are reviewed and discussed, and a speculative model for vent 1 eruptions is presented. Finally, fruitful avenues for further work are outlined.